Patent Application

of

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for

Method and Apparatus for Plasma-Mediated Thermo-Electrical Ablation

GOVERNMENT SPONSORSHIP

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FIELD OF THE INVENTION

The present invention relates to an apparatus for cutting materials including biological tissue by thermo-electrical ablation with the aid of a plasma produced around a cutting electrode and to a method for driving such electrode with appropriate pulses.

BACKGROUND

The cutting of materials with the aid of cutting electrodes energized by a suitable power source is a known technique that

is being successfully employed, e.g., in the field of electrosurgery. Typical electrosurgical devices apply a electrical potential difference or a voltage difference between a cutting electrode and a patient's grounded body (monopolar arrangement) or between a cutting electrode and a return electrode (bipolar arrangement) to deliver electrical energy to the area where tissue is to be cut. The voltage is applied either as a continuous train of high frequency pulses, typically in the RF range, or as direct current (DC).

The prior art provides a number of exemplary designs of bipolar electrosurgical electrodes. For example, U.S. Pat. No. 5,108,391 describes a bipolar treating apparatus with a first active electrode and a second return electrode having exposed distal ends to define a bipolar tip for electrosurgically treating tissue. U.S. Pat. No. 5,700,262 describes a bipolar electrode with fluid channels for performing neurosurgery. Additional information about bipolar electrosurgical devices and knives can be found, e.g., in U.S. Pat. Nos. 4,202,337 and 4,228,800 as well as numerous other open literature sources.

Depending on the conditions, the application of a voltage to a monopolar electrode or between the cutting and return electrodes of a bipolar electrode produces a number of physical phenomena. Most prior art devices take advantage of one of these phenomena to perform the cut. In particular, one class of devices uses a gas stream that is generated around the cutting electrode. For example, U.S. Pat. No. 5,217,457 describes an electrosurgical apparatus using a stream of gas that shrouds the electrode and

an electrosurgical apparatus incorporating this electrode for cutting biological tissue. U.S. Pat. No. 5,088,997 also teaches the use of a stream of gas for electrosurgical procedures for coagulating or cutting biological tissue. On the other hand, U.S. Pat. No. 5,300,068 teaches an electrosurgical apparatus for cutting tissue and for ablating occlusions using arc discharges produced on a monopolar electrode in response to a train of pulses. Taking advantage of a yet different phenomenon, U.S. Pat. No. 6,352,535 teaches a method and device for electro microsurgery in a physiological liquid environment that uses high voltage electrical discharges of sub-microsecond duration in a liquid medium to produce cavitation bubbles. The cavitation bubbles have a size in the sub-millimeter range and are used for high-speed precision cutting with an inlaid disc electrode.

In addition to taking advantage of different phenomena to perform the cut, prior art devices employ various techniques for generating and applying the voltage to the electrode or electrodes. U.S. Pat. No. 6,135,998 teaches an electrosurgical device which uses extremely short monopolar voltage pulses, typically shorter than 200 ns, to drive an electrode having an inlaid disc geometry. This invention attempts to mitigate some of the negative cavitation effects, such as the damaging jets formed after the collapse of the cavitation bubble. U.S. Pat. No. 5,108,391 describes a high frequency generator for tissue cutting and for coagulating in high-frequency surgery. This device uses an electric arc discharge to perform the cutting operation. U.S. Pat. No. 6,267,757 teaches a device which uses

radio-frequency (RF) ablation for revascularization. It employs a source, which delivers at least one burst of RF energy over an interval of about 1 to about 500 ms, and preferably about 30 to about 130 ms. This device has an elongated insulated, electrical conducting shaft with an uninsulated distal tip, which is configured to emit the RF energy. U.S. Pat. No. 6,364,877 also describes the use of high frequency pulses applied in a continuous manner. The teaching found in U.S. Pat. Nos. 5,697,090 and 5,766,153 suggests that a continuous train of high frequency pulses can be pulsed at a rate sufficient to allow the electrode to cool.

Unfortunately, despite all the above teachings, electrosurgical methods and apparatus generally suffer from an inability to control the depth of tissue damage (necrosis) in the tissue being treated. Most electrosurgical devices described above rely on a gas jet, an arc discharge or cavitation bubbles to cut, coagulate or ablate tissue. Such imprecise cutting methods cause tissue necrosis extending up to 1,700 μm into surrounding tissue in some cases.

In an effort to overcome at least some of the limitations of electrosurgery, laser apparatus have been developed for use in arthroscopic and other procedures. Lasers do not suffer from electrical shorting in conductive environments and certain types of lasers allow for very controlled cutting with limited depth of necrosis. U.S. Pat. No. 5,785,704 provides an example of a laser used for performing stereotactic laser surgery. Unfortunately, lasers suffer from limitations such as slow

operating speed, inability to work in liquid environments, high cost, inconvenient delivery systems and other defects that prevent their more universal application. For these reasons, it would be desirable to provide improved apparatus and efficient methods for driving an electrosurgical apparatus for ablating tissue in a highly controlled and efficient manner while minimizing tissue damage.

The prior art has attempted to provide for more controlled electrosurgery by relying on plasma-mediated cutting and ablation of soft biological tissue in conductive liquid media at low temperatures. The fundamentals of this approach, which is used predominantly in the continuous pulse regime, and various embodiments employing it are described in the patents of Arthrocare including U.S. Pat. Nos. 5,683,366; 5,697,281; 5,843,019; 5,873,855; 6,032,674; 6,102,046; 6,149,620; 6,228,082; 6,254,600 and 6,355,032. The mechanism of low temperature ablation is called "coblation" and is described as electric field-induced molecular breakdown of target tissue through molecular dissociation. In other words, the tissue structure is volumetrically removed through molecular disintegration of complex organic molecules into non-viable atoms and molecules, such as hydrogen, oxides of carbon, hydrocarbons and nitrogen compounds. This molecular disintegration completely removes the tissue structure, as opposed to transforming the tissue material from solid form directly to a gas form, as is typically the case with ablation (see U.S. Pat. No. 5,683,366). More specifically, this mechanism of ablation is described as being associated with two

factors: (1) "photoablation" by UV light at 306-315 nm and visible light at 588-590 nm produced by the plasma discharge; and (2) energetic electrons (e.g. 4 to 5 eV) can subsequently bombard a molecule and break its bonds, dissociating a molecule into free radicals, which then combine into final gaseous or liquid species (see U.S. Pat. No. 5,683,366). Surface temperature of tissue in this process is maintained between 40-70 °C. This type of ablation mechanism has low rate of tissue dissection and a very limited applicability to hard tissues such as, for example, bones.

Despite these new advances the electrosurgical techniques are still experiencing a number of problems remain. First and foremost, the amount of power required to operate the prior art cutting devices remains in a high range of several Watts which precludes applications of these devices to such delicate organs as an eye. Second, the devices exhibit large energy and heat losses. These high losses translated into excessive power deposition into the tissue being ablated. Additional heat losses to the hand piece are also substantial. Third, even the best prior art devices operating at the lowest power levels have difficulties cutting hard biomaterials like bones and non-conducting materials such as cellulose or plastics.

Increasingly sophisticated surgical procedures create a growing demand for more precise and less traumatic surgical devices. The critical importance and delicate nature of the eye makes the demand for precision and safety of intraocular microsurgical instrumentation particularly important. For these and other

reasons, it would be a major advance in the art to provide an apparatus and method for ablating materials at low power levels. It would be particularly useful to provide such apparatus and method that reduces heat losses to the material being cut as well as into the surroundings and, especially the hand piece. Furthermore, it would also be an advance to expand the range of materials that can be ablated to include biological tissue, cellulose and plastics.

OBJECTS AND ADVANTAGES

In view of the above shortcomings of the prior art, it is an object of the invention to produce a cutting apparatus and provide a method for operating it to achieve efficient thermal ablation at low power levels, e.g., ranging down to 10 mW, by overheating and evaporation in various types of materials including biological tissue. Specifically, it is an aim of the invention to minimize the damage zone produced during the cutting process by using plasma-assisted cutting and minimizing heat losses into the material being cut as well as the surroundings and the hand piece.

It is another object of the invention to provide a modulation format for pulsed operation of the cutting apparatus to minimize adverse effects in cutting biological tissue.

It is yet another object of the invention to reduce the voltage necessary for ionization of the gas to derive the plasma.

Yet another object of the invention is to provide a versatile cutting electrode geometry for efficient cutting and removal of material. Some of these electrodes and the driving waveforms are specifically designed for applications in eye surgery.

These and other objects and advantages will become apparent upon review of the following description and figures.

SUMMARY OF THE INVENTION

The objects and advantages of the invention are achieved by a method for cutting a material including conducting and non-conducting materials such as biological tissue, cellulose or plastic. During cutting the material is submerged in a conductive liquid medium. The method involves providing a cutting electrode with an elongate cutting portion and a return electrode. The elongate cutting portion has an aspect ratio of length to width larger than 1 and preferably larger than 5. A thin cutting electrode allows for dissection of tissue with low energy deposition. The two electrodes are immersed in the conductive medium and a voltage is applied between them such that the conductive liquid medium is heated to produce a vapor cavity around the elongate cutting portion and to ionize a gas inside the vapor cavity to produce a plasma. The presence of the plasma maintains electrical conductivity between the electrodes. The voltage applied between the electrodes is modulated in pulses having a modulation format selected to minimize the size of the vapor cavity, the rate of formation of the vapor cavity and heat diffusion into the material as the

material is cut with an edge of the elongate cutting portion of the cutting electrode.

The modulation format includes pulses having a pulse duration in the range from 10 μs to 10 ms. Preferably, the pulses are composed of minipulses having a minipulse duration in the range between 0.1 and 10 μs and an interval ranging from 0.1 to 10 μs between the minipulses. Preferably, the minipulse duration is selected in the range substantially between 0.2 and 5 μs and the interval between them is shorter than a lifetime of the vapor cavity. The peak power of the minipulses can be varied from minipulse to minipulse.

When the method is used for cutting biological tissue it is preferable to use minipulses with alternating polarity. In other words, the modulation format contains minipulses that exhibit alternating positive and negative polarities. This modulation format limits the amount of charge transfer to the tissue and avoids various adverse tissue reactions such as muscle contractions and electroporation. In fact, additional devices for preventing charge transfer to the biological tissue can be employed in combination with this modulation format or separately when the method of invention is applied in performing electrosurgery.

In the same or in an alternative method of the invention the minipulses are further made up of micropulses. When the modulation format includes micropulses it is preferred that they have a duration ranging between 0.1 and 1 μs.

It is well-known that spark discharges develop in advance of an arc discharge. In accordance with the invention it is preferable to adjust the modulation format to permit spark discharges while preventing arc discharges. For example, the modulation format such as minipulse duration and peak power are adjusted to permit spark discharges while avoiding arc discharges. Furthermore, the voltage and the modulation format are selected such that the temperature of the elongate cutting portion of the cutting electrode and of the plasma are maintained significantly above the boiling temperature of water. Preferably, the temperature of the elongate cutting portion is maintained between about 100 and 1,000 °C.

The invention further provides an apparatus for cutting materials submerged in the conductive liquid medium. The apparatus is equipped with the cutting electrode with the elongate cutting portion and return electrode. A voltage source is used for applying the voltage between the cutting and return electrodes to produce the vapor cavity with plasma. A pulse control is provided for controlling the modulation format of the voltage applied between the electrodes. The pulse control has a peak power control and a duration control for adjusting pulse power, pulse duration and pulse interval.

The shape of the cutting electrode and the elongate cutting portion can vary according to the material being cut. For a number of electrosurgical applications the elongate cutting portion should have a width between 1 μm and 200 μm and

preferably between 10 μm and 100 μm. The elongate cutting portion can have various cross sections including circular, e.g., it is in the form of a wire. In these cases the entire cutting electrode can be in the form of a wire electrode. Application of a thin wire as a cutting electrode allows for reduction of power required for tissue dissection and reduces the depth of the damage zone produced at the edges of the cut. In order to perform certain types of cuts the elongate cutting portion can have one or more bends. For example, in certain electrosurgical applications the elongate cutting portion can be L-shaped or U-shaped. In some embodiments the elongate cutting portion can form a loop, e.g., it can be a looped wire electrode. In some embodiments it is advantageous to provide a device for advancing the wire electrode such that a length of the wire used for cutting can be adjusted during the application, when required. Such adjustment affects the impedance of the electrode and can be used for control of power dissipation. In addition, a fresh portion of the wire can be extended to replace the eroded portion. In one particular embodiment, the elongate cutting portion and the terminal portion of return electrode are both shaped into a shape suitable for capsulotomy.

In embodiments where transferring charge to the material should be avoided, e.g., when the material being cut is biological tissue, the apparatus has a device for preventing charge transfer to the non-conducting material. For example, a circuit with a separating capacitor, e.g., an RC-circuit, can be used

for this purpose. The details of the invention are discussed below with reference to the attached drawing figures.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a three-dimensional view of an apparatus according to the invention employed in cutting biological tissue.

Fig. 2 is a graph illustrating a pulse modulation format according to the invention.

Fig. 3 is a graph indicating the qualitative dependence of the cavitation bubble diameter and heat diffusion on duration of the pulse.

Fig. 4A is a graph illustrating the conversion of electrical energy of the discharge (1 mJ) into the mechanical energy of the bubble measured as a function of pulse duration for the apparatus of Fig. 1.

Fig. 4B is a graph illustrating the cavitation bubble size, energy deposition and heat diffusion as a function of pulse duration for the apparatus of Fig. 1.

Fig. 5 is a photograph of the use of cutting electrode with elongate cutting portion for cutting paper.

Fig. 6 is a graph of a pre-pulse and post-pulse used in accordance with the invention.

Fig. 7 is a graph illustrating the use of micropulses in accordance with the invention.

Fig. 8 is a graph illustrating the use of minipulses of alternating polarity in accordance with the invention.

Fig. 9 illustrates an apparatus of the invention used in cutting a material.

Fig. 10 illustrates an apparatus of the invention using a shaped cutting electrode.

Figs. 11A-C are partial views of alternative embodiments in accordance with the invention.

Fig. 12 illustrates an apparatus of the invention designed for capsulotomy.

DETAILED DESCRIPTION

Fig. 1 illustrates an apparatus **10** for cutting a material **12** submerged in a conducting liquid medium **14**. In this embodiment material **12** is a biological tissue made up of various types of tissue including muscle tissue **12A**, nerve tissue **12B**, bone **12C** and soft tissue **12D**. In general, however, material **12** can be any conducting or non-conducting material which requires cutting and can include materials such as cellulose, e.g., wood and cellulose-based materials as well as various types of non-conducting plastics. Liquid medium **14** can be any type of electrolyte. In the present embodiment, liquid medium **14** is a physiological medium, for example an isotonic saline solution.

Apparatus **10** has a cutting electrode **16** with an elongate cutting portion **18**. In the present embodiment, entire cutting electrode **16** is in the form of a wire electrode with circular cross section defined by a radius r_e. The material of wire electrode **16** can be any suitable conductor such as a metal like Tungsten, Titanium, Molybdenum, etc. or an alloy. In the present embodiment electrode **16** is made of Tungsten wire. Cutting

electrode **16** is surrounded by an insulating layer **20** and a return electrode **22**. Insulating layer **20** can be any dielectric material or combination of materials such as ceramic, plastic, glass, and/or air that provide electrical insulation between electrodes **16** and **22**. Electrodes **16** and **22** are arranged coaxially along a center line **26**. Cutting portion **18** protrudes beyond insulating layer **20** and return electrode **22**. In fact, a length L of elongate cutting portion **18** is exposed. The aspect ratio of length L to width w ($w=2r_e$) of cutting portion **18** is at least 1 and preferably more than 5.

A voltage control unit **24** is connected to cutting electrode **16** and to return electrode **22**. Voltage control unit **24** has a voltage generator for producing a voltage to be applied between electrodes **16, 22**. Unit **24** also has a pulse control for pulsing the voltage in accordance with a predetermined modulation format, as described below. The pulse control has a peak power control and a duration control for adjusting a pulse power, a pulse duration τ and a pulse interval.

The operating principle of the method of invention is based upon formation of a thin layer of a plasma **28** around elongate cutting portion **18**. To achieve this goal, electrodes **16, 22** of apparatus **10** are immersed in conductive medium **14** where tissue **12** is submerged and a voltage is applied between electrodes **16, 22** such that medium **14** is heated to produce a vapor cavity **30** around cutting portion **18**. During heating an amount of medium **14** is vaporized to produce a gas **32** inside vapor cavity **30**. In the present case medium **14** is saline and thus gas **32** is composed

predominantly of water vapor, a small amount of oxygen and hydrogen and trace amounts of NaCl. The layer of gas **32** is ionized in the strong electric field around cutting electrode **16** to make up the thin layer of plasma **28.** Because plasma **28** is electrically conductive it maintains electrical conductivity between electrodes **16, 22**.

In contrast to the prior art, it is important that the size and rate of formation of vapor cavity **30** as well as heat diffusion into tissue **12** be minimized. The size and rate of formation of cavity **30** are related and can be minimized by modulating the voltage applied between electrodes **16, 22** by the pulse control of unit **24** in accordance with a modulation format. Specifically, pulse control modulates the applied voltage in pulses **34**, as shown in Fig. 2. The modulation format of pulses **34** is selected to minimize the size of vapor cavity **30,** the rate of formation of vapor cavity **30** and also heat diffusion into tissue **12**.

To better understand the principles behind selecting the modulation format to achieve this minimization we now refer to the qualitative graphs in Fig. 3. Graph **38** illustrates the radius around elongate cutting portion **18** to which heat diffuses as a function of duration τ of pulse **34**. As duration τ of pulse **34** increases heat diffuses deeper into tissue **12**. This diffusion of heat causes thermal damage to tissue **12** and it is to be avoided. It should be noted, that the application of a long train of very high frequency pulses, e.g., RF pulses, will effectively act as one long pulse whose duration is equal to the

entire duration of the pulse train. Hence, prior art devices operating in the continuous regime and applying RF pulses (see Background section) suffer from high heat diffusion and consequently cause large thermal damage to surrounding tissue.

Graph **40** illustrates the maximal radius of vapor cavity in this case also referred to as bubble **30** (see Fig. 1), or cavitation bubble, which is formed at constant pulse energy around cutting electrode **16**. Now, the radius of cavitation bubble **30** initially increases with increasing pulse duration τ and then decreases and approaches zero as duration τ of pulse **34** tends to infinity (continuous current). Graphs **38** and **40** intersect at a pulse duration τ_c at which heat diffusion is still relatively insignificant while the radius of bubble **30** is already small enough not to cause significant tissue damage. Thus, by choosing duration τ of pulse **34** in a range **42** around τ_c heat damage and mechanical damage due to cavitation bubble **30** are minimized. In fact, choosing duration τ of pulses **34** so as not to produce large cavitation bubble **30** is equivalent to minimizing the size and rate of formation of vapor cavity **30**. A person skilled in the art will appreciate that the exact shape of graphs **38**, **40** and range **42** will vary depending on specific parameters such the exact composition of tissue **12**, salinity of electrolyte **14** and geometry of electrode **16**.

Fig. 4A shows a graph **44** of the conversion of the electrical energy of the discharge for a discharge energy equal to 1 mJ and electrode **16** diameter of 25 μm into mechanical energy of bubble **30** measured as a function of duration τ of pulse **34**. Efficiency

of the conversion decreases with increasing duration τ of pulse **34** once pulse **34** is longer than about 3 μs. In Fig. 4B the radius of single bubble **30** is illustrated by graph **38′** as a function of pulse duration τ in a 1 mJ discharge. At pulse duration τ above 50 μs a sequence of bubbles is formed with maximal radii reducing with increasing duration τ, as depicted by separate rhombuses. Graph **48** represents the penetration depth into material **12** of electric field E(r), here equal to radius r_e of cutting portion **18**. Graph **40′** represents the radius around cutting portion **18** to which heat diffuses assuming constant temperature of cutting portion **18** in one dimensional geometry.

A range **42′** in which pulse duration τ is optimized and in which both cavitation and heat diffusion are comparable with field penetration depth is between 50 μs and 2 ms. Under different conditions range **42′** will vary, but optimal duration τ of pulses **34** will generally fall between 10 μs and 10 ms. In this range **42′** the size and rate of formation of vapor cavity **30** as well as heat diffusion into tissue **12** are minimized. The thermal damage zone in tissue **12** due to heat diffusion is dependent mostly on duration τ of pulse **34**. Specifically, varying duration τ of pulses **34** between 0.1 and 100 ms changes the depth of the heated zone in tissue **12** between 10 and 300 μm ranging from single cellular layer with no hemostatic effect to complete hemostasis in most of tissues **12A, 12B, 12C** and **12D**.

Referring back to Fig. 2, pulses **34** can be delivered in various modulation formats including continuous pulses or bursts of short pulses or minipulses **50**. Preferably, pulses **34** are

separated by a separation **49** of at least 1 ms, and preferably at least 10 ms while pulses **34** themselves are composed of a number of minipulses **50**, as shown. The amplitude and duration of minipulses **50** determine the spatial extent and density of plasma **28**. To avoid excessive overheating of tissue **12** the modulation format is adjusted so that plasma **28** is maintained at the regime of streamer and spark discharges but the arc discharges are prevented. Specifically, duration and peak power of minipulses **50** are adjusted to permit spark discharges and to prevent arc discharges. In most cases, limiting the duration of minipulses **50** to less than several μs will accomplish this goal. In fact, the duration of minipulses **50** should be kept in the range between 0.1 and 10 μs and preferably between 0.2 and 5 μs. The interval between minipulses **50** is preferably selected in the range between 0.1 and 10 μs. Such short times are sufficient for ionization and development of the spark discharges but not for creation of the arc discharge.

An arc discharge is a highly luminous and intensely hot discharge of electricity between two electrodes, in this case between electrode **16**, and more precisely its cutting portion **18**, and return electrode **22**. The arc discharge is initiated when a strong electric forces draw electrons from one electrode to the other, initiating the arc. It is typically a continuous discharge characterized by high current and low voltage across the arc. On the other hand, a spark discharge has a high voltage and short duration.

If the intervals between minipulses **50** do not exceed a lifetime of vapor cavity **30** the ionization will be maintained by minipulses **50** until vapor cavity **30** collapses. Hence, in any situation, the intervals between minipulses **50** should be kept shorter than the lifetime of vapor cavity **30**. For example, the lifetime of a 100 μm wide vapor cavity **30** is about 10 μs, thus minipulses **50** should be delivered at intervals not longer than 10 μs when working with such cavity width.

In contrast to prior art devices, apparatus **10** cuts tissue **12** using a side or edge of cutting portion **18**, i.e., the entire length L of cutting portion **18** is available for performing the cut. Rapid and efficient ablation of tissue **12** is achieved when the temperature of cutting portion **18** and layer of plasma **28** around it are maintained significantly above the boiling temperature of water. In order to ensure that such temperature is efficiently maintained cutting portion **18** is long and thin, i.e., has a small radius - a few tens of microns - and an aspect ratio (length to width) of at least 1 and preferably at least 5. Such thin cutting portion **18** also reduces the amount of heat flow through the metal back into a hand piece (not shown).

In fact, heat flow W through cutting portion **18** is equal to:

$$W = \chi \Delta TS / L \, ,$$

where $S = \pi d^2 / 4$ is the cross section area of cutting portion **18**. In the above equation χ is the coefficient of thermal conductivity and ΔT is the difference in temperature between the

hot and cold parts of wire electrode **16**, L is the length of cutting portion **18** and $d=2r_e$. Evaporation rate of tissue **12** is equal to:

$$V = Ldv,$$

where v is the velocity of advance of cutting portion **18** through tissue **12**. The amount of power deposited in tissue **12** to achieve such evaporation rate is:

$$P = V \cdot \rho(C\Delta T_1 + \delta),$$

where ρ is the density of tissue **12**, C is its heat capacity, ΔT_1 is the temperature rise from ambient to 100 °C, and δ is the specific heat of evaporation (for tissue mostly composed of water the specific heat of evaporation of water $\delta=2.26\times10^3$ J/g can be used in the calculation). To prevent cooling of cutting portion **18** and of layer of plasma **28** by heat transfer via electrode **16**, power deposition P should be kept significantly larger than the heat flow W, i.e., P>>W. In the present embodiment electrode **16** is made of Tungsten which has a heat conductivity χ=178 W/mxK, ΔT_1=70 °K and cutting portion **18** is advanced through tissue **12**. For example, at ΔT=250 °K and v=1 mm/s one obtains the condition $L^2/d>>14$ mm from the above equations. Therefore, to efficiently prevent cooling when cutting portion **18** has a length L=1 mm the diameter $d=2r_e$ of cutting portion **18** should be less than 70 μm. For ΔT=70 °K and the rest of the parameters remaining the same we will obtain the conditions $L^2/d>>4$ mm. This means that a 1 mm long cutting portion **18** should not be thicker than 250 microns.

The temperature of cutting portion **18** can be maintained as low as about 100 °C, but it is preferably much higher, ranging up to 1000 °C. In this temperature range tissue **12** is rapidly evaporated and thus ablated. Due to the turbulent flow of liquid boiling at the edges of vapor cavity **30** the interface with tissue **12** is only minimally overheated and damaged.

In the regime of heating produced by plasma **28** the temperature of cutting portion **18** is stabilized by a naturally occurring negative feedback mechanism as follows. In the areas where the vapor sheet of cavity **30** becomes thinner, the electric impedance is reduced and thus more current flows. The increased current results in increased generation of Joule heat in that area, and thus more electrolyte **14** is evaporated thereby increasing the thickness of vapor cavity **30** in that area. This mechanism stabilizes the thickness of vapor cavity **30** around cutting portion **18** and the thermal conditions of cutting portion **18**. When tissue **12** is brought into ionized vapor cavity **30**, thus reducing its thickness in that area, more current flows into tissue **12** than into plasma **28**, since the impedance of tissue (which is typically similar to that of electrolyte **14**) is much lower than that of plasma **28**. Thus, more heat is generated in the area where tissue **12** is positioned inside vapor cavity **30**.

Application of thin elongated electrode (for example a wire electrode) allows for minimization of the amount of material evaporated during tissue dissection as well as for minimization of the depth of the damage zone produced at the edges of the

cut, as shown below. In the present embodiment, the electric field E(r) around cylindrical cutting portion **18** is reciprocal to the distance from it, and the density of Joule heat generated in liquid by the discharge is reciprocal to the square of that distance. Thus, thinner cutting portion **18** results in a more confined energy deposition. In fact, the electric field E(r) around cylindrical cutting portion **18** scales with distance r as follows:

$$E = \frac{E_e r_e}{r},$$

where E_e is the value of the electric field on the surface of cutting potion **18**. Thus, the difference in voltage on the surface of cutting portion **18** and at a distance R from electrode **16** is:

$$U_e - U_R = \int_R^{r_e} E(r)dr = E_e r_e (\ln R - \ln r_e).$$

The electric field becomes spherical at distances larger than length L of cutting portion **18**, and thus it can be assumed that the electric potential drops to zero for distances larger than L. Therefore, the electric field E_e at the surface of cutting portion **18** is:

$$E_e = \frac{U_e}{r_e(\ln L - \ln r_e)}.$$

The power density w of the Joule heat generated in electrolyte **14** is then:

$$w = j^2\gamma = \frac{E_e^2}{\gamma} = \frac{U_e^2}{r_e^2(\ln L - \ln r_e)^2\gamma},$$

where j is the current density and γ is the resistivity of electrolyte **14**. The minimal energy density for overheating of the surface layer of electrolyte **14** (assumed to be water) by pulse **34** of duration τ is:

$$A = w \cdot \tau = \rho \cdot C \cdot \Delta T,$$

where ΔT is the total temperature rise in the surface layer of electrolyte **14** during pulse **34**, ρ is the density of water and C is its heat capacity. Therefore, the voltage U required for initiation of vaporization during pulse **34** of duration τ is:

$$U = r_e(\ln L - \ln r_e)\sqrt{\rho \cdot C \cdot \Delta T \cdot \gamma/\tau}.$$

The voltage U and associated energy deposition can be reduced by decreasing the radius r_e of cutting portion **18**. In general, ambient temperature is about 30 °C when operating in biological tissue **12** of a live subject, boiling temperature is 100 °C, ρ=1 g/cm^3, C=4.2 J/(g•K) and γ≈70 Ohm•cm. With these values we obtain A≈300 J/cm^3 and U=260 V for pulse **34** of duration τ=0.1 ms, r_e=25 μm and L=1 mm.

Since the electric field is reciprocal to the distance from the cylindrical electrode, the field efficiently penetrates into the electrolyte to the depth similar to the radius of the electrode. This minimal amount of energy required for creation of the vapor cavity around the electrode is:

$$A = w \cdot \tau = \rho \cdot C \cdot \Delta T \cdot \pi \cdot d^2 \cdot L,$$

where *d* is the diameter of the electrode. Minimal depth of the damage zone at the edges of the cut will thus be similar to the radius of the electrode. Thus, reduction in radius of the electrode results in reduction in the power consumption and in the width of the damage zone produced at the edges of the cut. The threshold voltage U_{th} required for reaching the threshold electric field E_{th} to ionize gas **32** and produce plasma **28** is:

$$U_{th} = E_{th} r_e \ln(R/r_e),$$

where R is the radius of vapor cavity **30**, as shown in Fig. 1. Threshold voltage U_{th} can be decreased by reducing radius r_e of cutting portion **18**. This also results in a lower power dissipation and consequently in a smaller damage zone in tissue **12**.

Vapor cavity **30** filled with plasma **28** and surrounding cutting portion **18** of cutting electrode **16** serves three major functions. First, it thermally isolates cutting electrode **16** from electrolyte **14** thus allowing for efficient heating. Second, the electric impedance of plasma **28** is much higher than that of

tissue **12**, thus Joule heating is generated mostly in plasma **28** and not in the surrounding liquid environment. Third, since both electrical and thermal conductivity of tissue **12** is much higher than that of a vapor (gas **32**), when tissue **12** is introduced inside vapor cavity **30** with plasma **28** it attracts both electric current and heat flow, which results in fast overheating and evaporation.

Another advantage of the cylindrical geometry of cutting electrode **16** as compared to prior art point sources (inlaid disc geometry) is that it allows for cutting tissue **12** with the side edge of cutting portion **18**. Prior art point sources (see U.S. Pat. No. 6,135,998) produce a series of perforations when a train of pulses is applied. These perforations do not always form a continuous cut leaving behind bridges between the edges of the cut. To dissect these bridges the secondary scans are required and targeting these thin and often transparent straps of tissue is very difficult and time consuming. Cylindrical cutting portion **18** solves this problem by enabling the cutting by its edge and not only by its end or tip.

In order to reduce unnecessary energy deposition, e.g., during electrosurgery, the voltage of source **24** can be set to a level which is sufficient for ionization of only a thin layer of vapor. Thus, in areas where vapor cavity **30** is too large (typically above several tens of microns) no plasma **28** will be formed. As a result, ionization and formation of plasma **28** will only take place in the areas of proximity or contact between generally conductive tissue **12** and conductive cutting portion

18. In other parts of vapor cavity **30** gas **32** will not be ionized and thus it will electrically insulate cutting electrode **18** preventing heat deposition into the surrounding environment. Fig. 5 illustrates cutting electrode **16** with cutting portion **18** of radius r_e=25 μm immersed in isotonic saline solution touching the edge of a material **52**. This figure shows clearly the formation of plasma **28** at the point of contact with material **52**. In this case material **52** is made of cellulose and is in fact a sheet of paper. Cutting portion **18** is touching an edge of paper **52** that is about 250 μm thick. As is clearly seen, plasma **28** is generated only in the area of contact between cutting electrode **18** and paper **52**.

To further reduce the energy deposition cavity **30** can be created by electrochemical generation of gas **32**, i.e., by electrolysis of water, rather than by its vaporization. For this purpose the pulse control and source **24** can vary the voltage between parts of the pulse or even between two successive pulses, as shown in Fig. 6. First, source **24** applies a pre-pulse **54** of relatively low voltage. This low voltage should be sufficient for electrolysis and can be in the range of several tens of Volts. In accordance with well-known principles, the application of such low voltage will yield oxygen gas on the anode and hydrogen gas on the cathode. The user can choose whether to use oxygen or hydrogen as gas **32** by selecting the polarity of pre-pulse **54**, such that cutting portion **18** is either the anode or cathode. It should be noted, that applying a pulse composed of minipulses with alternating polarity (see Fig. 8 and below description) will generate a mixture of oxygen and hydrogen.

Next, pulse control and source **24** increase the voltage to a relatively high level in a post-pulse **56**. The voltage of post pulse **56** can be in the range of several hundred Volts to complete the formation of vapor cavity **30** and to ionize gas **32** to form plasma **28**. A sequence of combination pulses containing pre-pulse **54** and post-pulse **56** can be used to drive apparatus **10**. Alternatively, a single combination pulse can be followed by a series of regular pulses **34** composed of minipulses **50**, as described above. Embodiments of the method taking advantage of electrochemical generation of gas **32** around cutting portion **18** of electrode **16** obtain a substantial pulse energy reduction.

The rate of evaporation of electrolyte **14** depends on its temperature. There is always a delay between the moment when electrolyte **14** reaches boiling temperature (boiling temperature of water) and the moment when formation of vapor cavity **30** disconnects the current flowing through electrolyte **14** between electrodes **16, 22**. When vapor cavity **30** forms, gas **32** stops the current flow and prevents further heating. Just before this time an additional energy is deposited that leads to overheating of electrolyte **14** and thus to explosive (accelerated) vaporization. This effect results in formation of a larger vapor cavity **30** and turbulence around cutting portion **18** of electrode **16**. To prevent such overheating the energy for initial boiling should be delivered at a lower voltage, but as soon as vapor cavity **30** is formed, the voltage should be increased to achieve fast ionization of gas **32**. Several solutions can be employed to address this problem.

In accordance with a first solution, a low impedance line **58**, as indicated in dashed line in Fig. 1, is used instead of a standard electrical connection between the output of pulse generator in unit **24** and cutting electrode **16**. In accordance to well-known principles, low impedance line **58** will cause the rising edge of a pulse to be reflected from the output end if the output impedance is high. This condition occurs when vapor cavity **30** is formed and not while electrode **16** is in direct contact with electrolyte **14**. The reflection will oscillate within line **58** with a period determined by its length, and will form a high frequency (several MHz) modulation.

Fig. 7 illustrates the effect of line **58** on minipulses **50** in a pulse **34**. The first set of minipulses **50** does not experience any changes because at this time the output impedance is still low (vapor cavity **30** not yet formed). Once vapor cavity **30** is formed reflection occurs and micropulses **60** are generated. As a result, each minipulse **50** gives rise to a series of micropulses **60**. The length of line **58** is selected such that micropulses **60** have a duration τ_μ in the range between 0.1 and 1 μs. The voltage of micropulses **60** is twice as high as that of minipulse **50**. This doubling in voltage of micropulses **60** is beneficial because it aids in ionizing gas **32** to form plasma **28** more rapidly and depositing more energy in plasma **28** than it was possible with minipulse **50** at the lower constant voltage level. That is because energy deposition increases as the square of the voltage and only linearly with the amount of time the voltage is applied. Hence, although micropulses **60** are applied at

electrode **16** only about half the time of a minipulse **50**, their doubled voltage raises the energy deposition by a factor of four.

In accordance with another solution an increase in the rate of ionization of gas **32** is achieved by adding a ballast resistor **62** in series with the load, as shown in dashed lines in Fig. 1. The resistance of resistor **62** ($R_{ballast}$) is selected to be higher than the impedance of the discharge in electrolyte **14** ($R_{electrolyte}$) but lower than in the ionized vapor or gas **32**. As a result, the heating of electrolyte **14** before evaporation will proceed at a lower voltage U_{low}:

$$U_{low} = U/\left(1 + R_{ballast}/R_{electrolyte}\right).$$

The reduced voltage will slow the boiling and cause formation of thinner vapor cavity **30**. After evaporation the impedance will greatly increase, resulting in an increase of the discharge voltage to a high value U_{high}:

$$U_{high} = U/\left(1 + R_{ballast}/R_{vapor}\right).$$

At this high voltage ionization of gas **32** will proceed rapidly. Specifically, when cutting portion **18** has a diameter of 50 µm and its length L=1 mm the impedance of the discharge in saline **14** is about 500 Ω, while in plasma **28** it is about 6 kΩ. Thus, for example, a ballast resistor of 1 kΩ will provide output voltages of U_{low}=U/3 and U_{high}=U/1.17, respectively. The lower limit to the voltage applied during the heating phase is set by

how much the duration of minipulses **50** and pulses **34** can be increased without unacceptable thermal damage to tissue **12** is caused by increased heat diffusion.

In yet another embodiment the method of invention is adapted specifically for cutting biological tissue **12** containing muscle tissue **12A** and nerve tissue **12B**. It is known that electric excitation of nerve tissue **12B** leads to contractions in muscle tissue **12A**. In order to avoid contraction of muscle tissue **12A** and reduce the risk of electroporation of adjacent tissue the method of invention calls for limiting and preferably stopping any charge transfer to tissue **12**. This is achieved by using minipulses **50** of alternating positive and negative polarities, as illustrated in Fig. 8. Low impedance line **58** can also be used to generate micropulses **60** when vapor cavity **30** is formed.

The polarities are set by the voltage source of unit **24** in accordance with well-known electronics techniques. In the present embodiment the alternating polarities can be produced by a separating capacitor (not shown). The discharge time constant of the RC circuit, where R is the resistance of the discharge, should not exceed the excitation time of nerve cells in nerve tissue **12B** at the applied voltage level. A person skilled in the art will appreciate that exact RC time constant will have to be adjusted on a case-by-case basis. In general, however, contractions of muscle tissue **12A** will be prevented at a voltage level of 500 Volts if the discharge time does not exceed 1 μs. When cutting portion **18** has a diameter of 50 μm and length L=1 mm the electrical impedance is about 500 Ω, and hence the

capacitance of capacitor should not exceed 2 nF. It should be noted that in addition to preventing muscular contractions, alternating polarity of minipulses **50** reduces the effect of electroporation, as compared to direct current (DC) (only positive or only negative voltage) pulses.

Various alternatives can be introduced to the apparatus of invention depending on the material being cut and the type of cut required. For example, in Fig. 9 a cutting electrode **80** of an apparatus analogous to apparatus **10** is used for performing a circular incision **84** in a material **82**. The return electrode and liquid conducting medium are not shown in this drawing. Material **82** is a thin sheet of plastic or biological material. When used for performing biopsy, a cylindrical biopsy can be easily obtained in this manner without bleeding.

Fig. 10 illustrates a cutting electrode **90** having two bends **92, 94** to form a U-shaped electrode. The return electrode and liquid conducting medium are not shown in this drawing. Cutting electrode **90** is used for removing a large amount of a material **96** with a single cut. U-shaped cutting electrode **90** can be used to minimize the damage to tissue in electrosurgery and to maximize the lifetime of cutting electrode **90**. In an alternative version a cutting electrode with a single bend can be used to make and L-shaped cutting electrode. In general, bends at various angles can be introduced to cutting electrode to perform any desired type of cut, to approach tissue at various angles and to manipulate the tissue before and during the cutting.

Fig. 11A illustrates a portion of yet another apparatus **100** having a mechanism **102** for advancing a cutting electrode **104**. In this embodiment cutting electrode **104** is a wire electrode. Return electrode **106** is in the form of two capillaries through which wire electrode **104** is threaded. Capillaries **106** can be used for delivering an electrolyte and/or aspiring fluids during electrosurgery, i.e., capillaries **106** can be used for irrigation and suction. Cutting electrode **104** forms a loop **108** for cutting tissue in accordance with the method of the invention. Mechanism **102** allows the user to refresh cutting electrode as needed during operation. Exposure time of wire electrode **104** outside capillaries **106** should be smaller than its erosion lifetime. It should be noted that mechanism **102** can be used in other embodiments for both advancing and retracting the cutting electrode as necessary to maximize its lifetime and/or retract an eroded electrode.

Fig. 11B illustrates a portion of an apparatus **110** using a wire electrode **112** threaded through capillaries **114**. Capillaries **114** serve the dual function of return electrode and channels for delivering and aspiring fluids during operation. Apparatus **110** can be used as a frame saw, as required in electrosurgical applications. Fig. 11C illustrates a portion of still another apparatus **120** functioning as a stationary scissors for both lifting and cutting of tissue. Apparatus **120** has a cutting electrode **122** in the form of a wire threaded through two capillaries **124** functioning as the return electrode. Mechanism **102** allows the user to refresh cutting electrode as needed

during operation. Exposure time of wire electrode **112** outside capillaries **114** should be smaller than its erosion lifetime. A projection **126** is used for lifting of tissue. Both apparatus **110** and apparatus **120** are operated in accordance with the method of the invention.

Fig. 12 illustrates a portion of an apparatus **130** specifically designed for capsulotomy. An electrosurgical probe **132** for capsulotomy has a shape similar to the mechanical tools used for capsulotomy in order to make its application easy and convenient for surgeons who are used to such mechanical tools (comparison is shown in the top photograph). Probe **132** has an insulator **134** with external diameter varying between 0.1 and 1 mm, which has a bent tip **136** at the end. A cutting electrode **138** with a diameter varying between 10 to 200 microns protrudes from insulator **134** by a distance varying between 20 microns to 1 mm. A return electrode **140** can be either a concentric needle or an external electrode attached to the eye or somewhere else to the body of the patient. Apparatus **130** protects the tissue located above the lens capsule (cornea and iris) (not shown) from accidental contact with cutting electrode **138** thus ensuring its safe use during capsulotomy.

The apparatus and method of the invention ensure efficient thermal ablation at low power levels, e.g., ranging down to 10 mW by overheating and evaporation. Devices built in accordance with the invention can be used for cutting various types of materials including biological tissue while minimizing the damage zone and minimizing heat losses into the material being

cut as well as the surroundings and the hand piece. The voltages necessary for producing the plasma are reduced significantly in comparison to prior art devices. Because of such power efficiency and low thermal damage the apparatus of invention and method for operating it can be adapted to numerous applications in surgery on very sensitive organs, such as the eye. For example, the apparatus of invention can be used for: (a) dissection of membranes and cutting retina in vitreoretinal surgery, (b) capsulotomy, (c) lensectomy, (d) iridectomy, (e) trabeculectomy.

A person skilled in the art will recognize that many extensions and alternative embodiments of the invention are possible and that the full breadth of the invention is hence defined by the scope of the appended claims and their legal equivalents.